

# **Acoustic Testing of Flight Hardware Using Loudspeakers: How Much Do We Know About This Method of Testing?**

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## **ABSTRACT**

Loudspeakers have been used for acoustic qualification of spacecrafts, reflectors, solar panels, and other acoustically responsive structures for more than a decade. Even though a lot of hardware has been acoustic tested using this method, the nature of the acoustic field generated by controlling an ensemble of speakers with and without the hardware in the test volume has not been thoroughly investigated. Limited measurements from some of the recent speaker tests used to qualify flight hardware have indicated significant spatial variation of the acoustic field within the test volume. Also structural responses have been reported to differ when similar tests were performed using reverberant chambers. Unlike the reverberant chamber acoustic test, for which the acoustic field in most chambers is known to be diffuse except below several tens of Hz where acoustic standing waves and large spatial variations exist, the characteristics of the acoustic field within the speaker test volume has not been quantified. It has only been recently that a detailed acoustic field characterization of speaker testing has been made at Jet Propulsion Laboratory (JPL) with involvement of various organizations. To address the impact of non-uniform acoustic field on structures, a series of acoustic tests were performed using a flat panel and a 3-ft cylinder exposed to the field controlled by speakers and repeated in a reverberant chamber. The analysis of the data from this exercise reveals that there are significant differences both in the acoustic field and in the structural responses. In this paper the differences between the two methods are reviewed in some detail and the over- or under-testing of articles that could pose un-anticipated structural and flight qualification issues are discussed. A framework for discussing the validity of the speaker acoustic testing method with the current control system and a path forward for improving it will be provided.

**KEY WORDS:** Acoustics, vibro-acoustics, acoustic/structural coupling, direct acoustics, reverberant chambers, and loudspeakers.

## **INTRODUCTION**

For most spacecraft and many of their components, acoustic testing is required to attain their flight qualification. For the last several decades reverberant acoustic testing method has been used to qualify flight hardware for acoustic environments. The acoustic field controlled in most chambers provide diffuse field, except at low frequencies. The diffusivity of a chamber can be assessed by considering resonance peaks that are closer than the bandwidth associated with any one peak. The cut-off frequency of which this may happen is given by Schroeder equation<sup>1</sup> and is estimated for the JPL chamber with approximately 10,000 ft<sup>3</sup> to be ~130 Hz and for a chamber with 1,000 ft<sup>3</sup> volume to be ~ 320 Hz. Therefore, depending on the size of the chamber and flight hardware the accuracy of acoustic qualification of flight hardware below the cut-off

frequency is questionable and is impacted by acoustic standing waves. The acoustic standing waves coupling to the acoustically responsive structural modes can result in increased structural responses. This effect is discussed in the paper by Kolaini et al. in some detail<sup>2</sup>.

It has only been relatively recently that the direct acoustic field testing method has been used in flight hardware qualification testing<sup>3-6</sup>. The first such testing was reported by Scharton et al. using the QuikSCAT spacecraft<sup>3-4</sup>. Due to the schedule constraints a series of speakers surrounding the QuikSCAT spacecraft were used to control the acoustic field within the speaker volume to the required environments. The characterization of the induced acoustic field was not made at the time. Since the QuikSCAT speaker testing, several dozen flight qualification tests have been performed using this method. It is very clear that this method offers some advantages over reverberant testing, which are outlined in Larkin & Walen, 1999<sup>5</sup>. The chief among the advantages is the schedule impact, where the loudspeakers could be brought to where the spacecraft is being assembled and acoustic tested without delays for transportation of the hardware to a different test site. However, the direct acoustic field characteristics can be strongly affected by test setup factors, especially variations in speakers' layout<sup>7</sup>, the control microphone locations and numbers, and the hardware itself. Unfortunately, most of the speakers' tests to date were performed without the characterization of the acoustic field. In general, most test conductors do not spend adequate time to understand the field and assess the potential exposure of the flight hardware to under- and over-testing conditions. Up to this date the speakers used to generate the acoustic field were controlled using a multi-input-single-output (MISO) scheme. It is only after the loudspeakers testing at JPL that a multi-input-multi-output (MIMO) control scheme has been considered (see a few related papers discussing this method at this conference). Unlike diffuse acoustic tests, guidelines for speaker testing do not exist. Testing is performed based on a limited knowledge of the acoustic field generated by the speakers and ad hoc approaches are implemented in order to obtain the desired sound field.

The structural responses induced by direct field testing often differ significantly from those induced by diffuse field testing, usually at specific frequencies or a range of frequencies<sup>2,8</sup>. The differences in the two methods of acoustic testing were discussed in a recent paper, where physical parameters attributed to them at lower frequencies were discussed. One of the parameters that strongly influence structural responses is the acoustic standing wave coupling with the structural modes<sup>2</sup>.

To characterize the acoustic field generated by speakers using the MISO control system a series of tests was performed at JPL with involvement from several institutions. A simple aluminum panel with an electronic box attached to it and an aluminum cylinder were used as test articles. These articles were also acoustic tested at JPL's reverberant chamber to the same acoustic specification levels as the speakers' test. The differences in the acoustic fields generated by the speakers and reverberant acoustic fields and their impacts on the structural responses are discussed in this paper. The results discussed and the conclusions provided herein may be helpful in the preparation of guidelines for the direct acoustic field testing, a subject that will be discussed at the Aerospace Testing Seminar.

## **EXPERIMENTAL SETUP**

The speakers' test (referenced by others as direct field acoustic testing with acronym as DFAT) was performed at JPL environmental testing facility during March 23-25, 2010. The speakers, woofers, and control system were provided by Maryland Sound International (MSI). They were responsible for setting up the testing configuration as shown in Figure 1. A series of control microphones (up to 8) were used in different configurations to control the sound field within the speakers to an overall sound pressure level (OASPL) of up to 145 dB. Most of the runs were performed using an OASPL of 140 dB. In addition to using eight control microphones another 8 were spread within the testing volume to obtain the sound pressure spatial variation. Finally an array of 36 microphones, rigged up very quickly, were also used and positioned in several locations to obtain the detail sound pressure variation within the testing volume. The array consisted of a rubber net attached to a frame where microphones were carefully tie downed to the net in an approximately 8x8 inch grid pattern (see Figure 1c). The microphones were held in place by using small neoprene pieces. This helped to de-couple the potential vibration of the net and microphones and reduced the unnecessary noise that could have resulted from such coupling. The sound pressure levels (SPLs) measured by these microphones are used to discuss the acoustic field generated using the MISO control scheme and the arrangement shown in Figure 1.

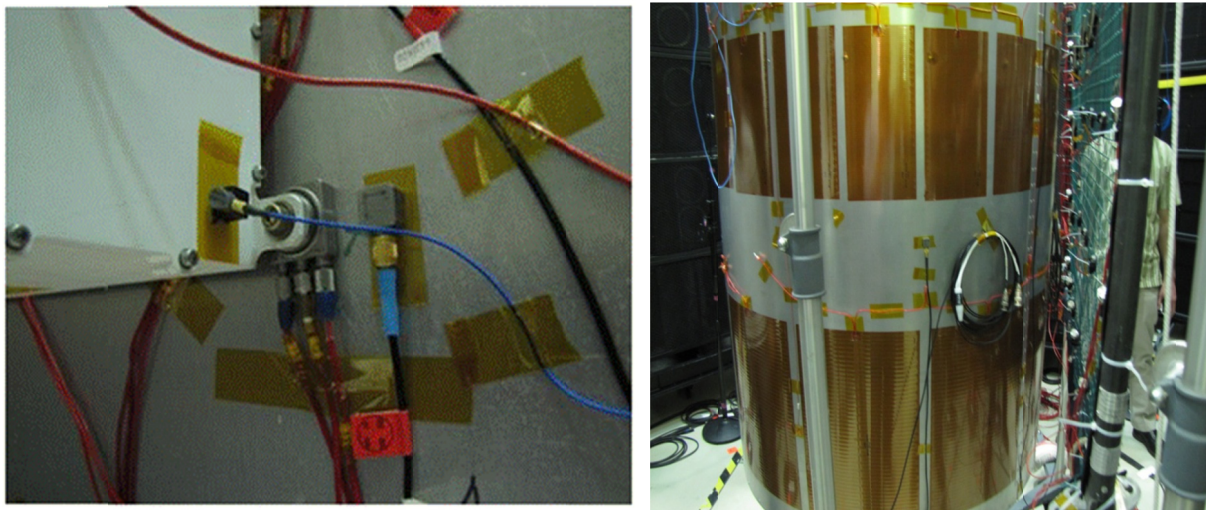


**Figure 1:** The speakers and woofers arrangement a) captured using a wide angle lens camera, b) an image of the speaker testing volume used for JPL tests, and c) an image of microphone array.

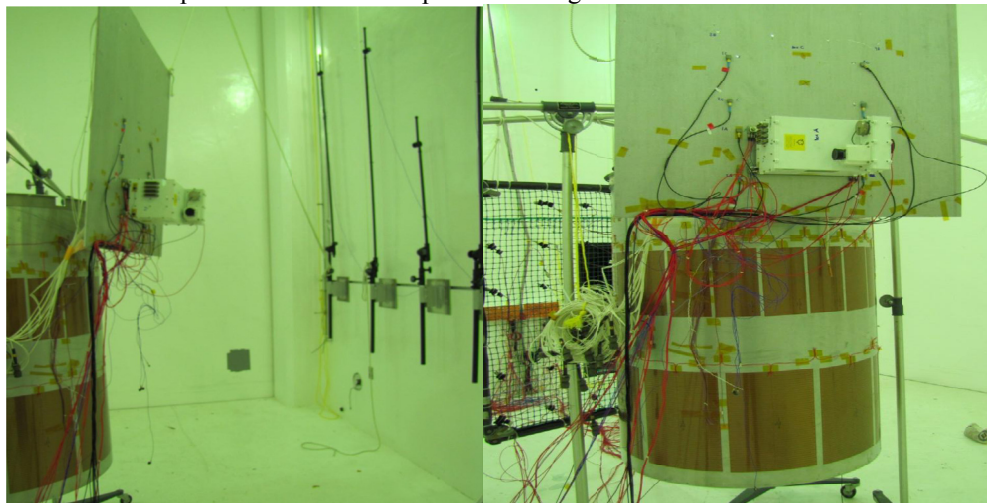
Two simple test articles, an aluminum panel with an electronic box and a 3-ft diameter cylinder kept close to the panel to mimic a small spacecraft, were used to measure the structural responses under the sound field generated by the loudspeakers. These test articles were instrumented with a series of triaxial accelerometers. Force gages were also used to measure the force responses at the electronic box interface to the panel as shown in Figure 2. The responses from these force gages will be used to discuss the differences in the box interface forces using the loudspeakers and the reverberant acoustic testing. The testing conditions were repeated in the JPL reverberant acoustic chamber as depicted in Figure 3.



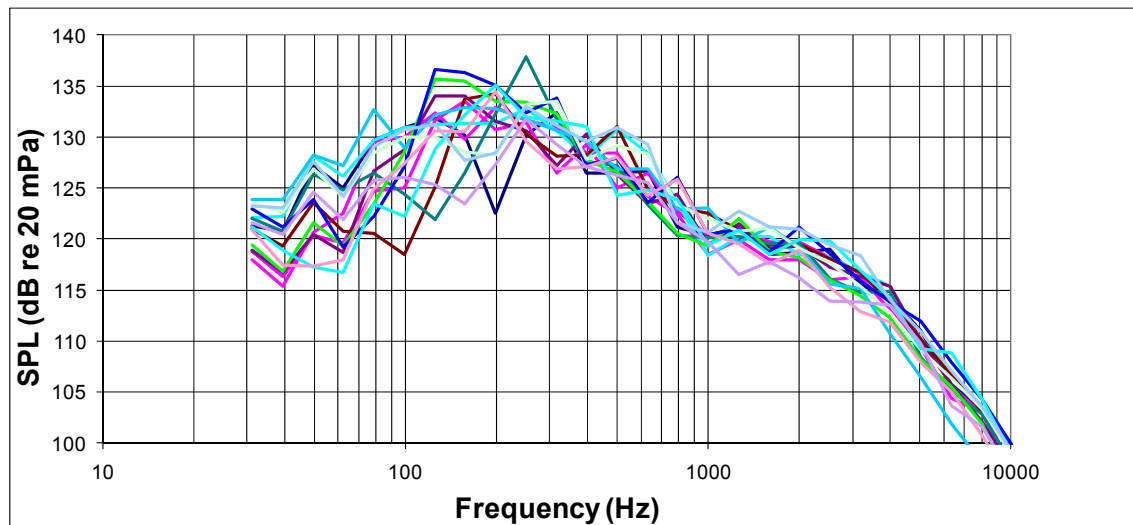
Issues related to the lack of uniform sound pressure field produced by speakers have been discussed within the community since the inception of this method of testing. As an example consider the SPLs measured using several control microphones from a recent spacecraft loudspeakers acoustic qualification test. The significant variations in the SPLs from a few tens of Hz to several hundred of Hz were observed from this test as depicted in Figure 4. Unlike reverberant acoustic testing where the significant spatial variations are confined to frequencies below 100 Hz in most existing chambers, the data from speakers testing has shown to have significant variation between several tens of Hz to several hundreds of Hz, where most flight components are impacted. The central issue discussed in this paper is the SPL spatial variation and its impact on the structural responses. Other issues such as the control strategy, control microphone locations and numbers, pressure waves interferences, acoustic standing waves, near field and far field acoustic waves, distance between speakers and the test hardware, impact of the hardware on the SPL, vibro-acoustic predictions, etc. will be discussed in papers prepared in the near future.



**Figure 2:** An aluminum panel with an electronic box with force gages installed at the box/panel interfaces and a 3-ft cylinder used as test articles positioned within the speakers testing volume.



**Figure 3:** The aluminum panel with electronic box and the cylinder acoustic tested using the JPL reverberant chamber.



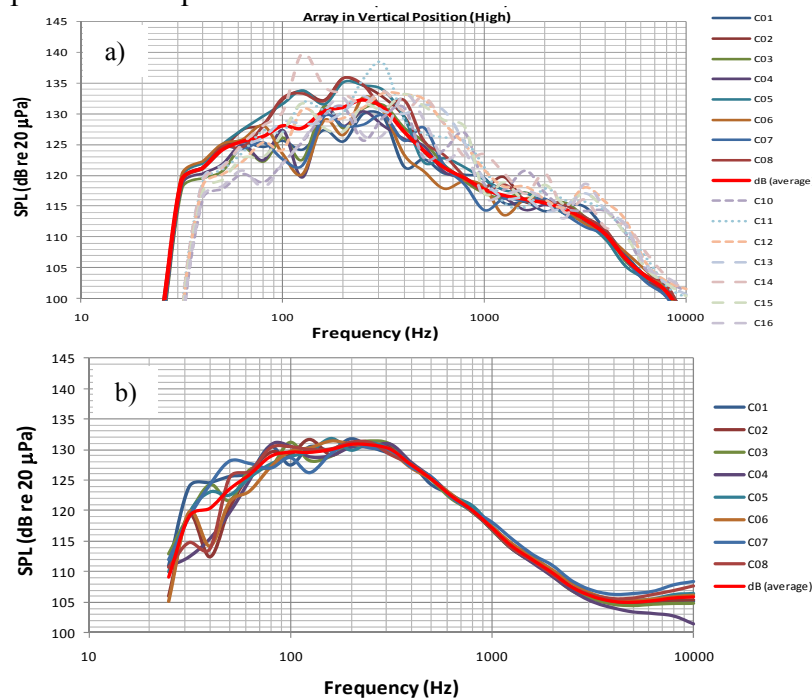
**Figure 4:** The spatial variation of the SPLs measured from a spacecraft that recently underwent acoustic qualification test using speakers.

## ACOUSTIC FIELDS: SPEAKERS VS. REVERBERANT CHAMBER

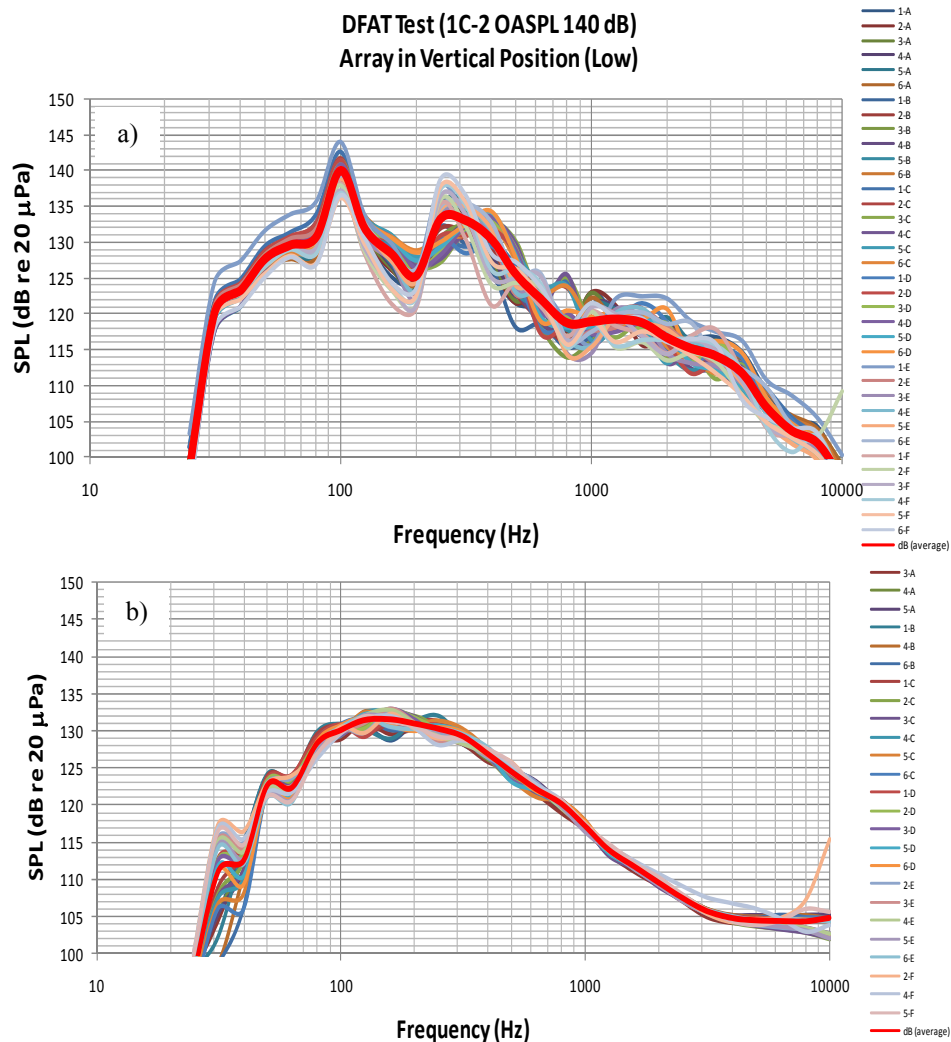
The sound pressure levels from the 8 control microphones for the loudspeakers test without test articles present are plotted in Figure 5a. The sound pressure levels from the 8 monitor microphones are also shown in this figure. The control microphones were placed on a circle 36 inches in radius from the center of the testing volume in a plane parallel to the floor with some of them located 43, 62, and 81 inches from the floor. The loudspeakers control microphone locations discussed in the subsequent few figures were kept the same with and without the test articles in the testing volume. Eight control microphones randomly spaced in the reverberant chamber and kept at least 2-ft from chamber walls and several feet from the test articles were used to control the SPLs within the chamber. The reverberant chamber sound pressure levels from the 8 microphones are shown in Figure 5b.

Figures 6a&b show the sound pressure levels measured using the microphone array without the test articles present, with the array placed close to where the cylinder would have been (see Figure 3) in both the speakers and reverberant chamber tests. Several important observations are made from these figures. First, the spatial SPL variations are significant across broader frequencies in the case of the speakers test with up to 20 dB variations as are shown in Figures 5a and 6a. The over test near 130 Hz, between 210 to 500 Hz, and under test close to 200 Hz are very clear from Figures 5a and 6a. These are frequency ranges that would structurally impact most flight components. The reverberant chamber SPLs on the other hand have insignificant spatial variation above the chamber cut-off frequency (Schroeder frequency). The variation below this frequency is due to the fundamental acoustic standing waves<sup>7</sup>. Second, the variation in the loudspeakers test SPLs provides peaks and valleys when compared to the average levels (See Figure 6a). The existence of such peaks and valleys provide under/over testing conditions that will inevitably impact acoustically responsive test articles in a significant way. Third, in a tight speaker testing volume the spectral characteristics shown in Figures 5a and 6a change with the hardware (see discussions later in this section); therefore, re-calibrating the required field in the presence of flight hardware may increase the structural risk.

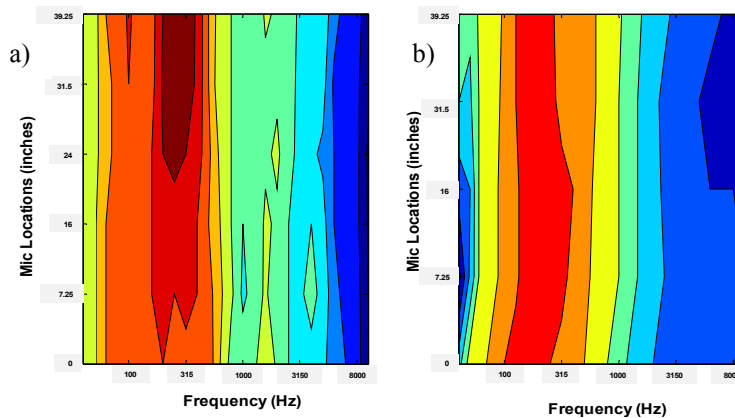
The spatial variation of the SPLs can be further visualized by 3-d plotting the data from microphone array obtained from both the chamber and speaker tests (Figures 7a&b). The horizontal axis in each plot shown in these figures is the 1/3 octave band frequency in Hz and the vertical axis is the location of the microphone array with respect to the floor. In these figures data are shown from one vertical row of microphones in the array taken from speakers and chamber tests. Again these figures provide compelling evidence on the nature of the sound pressure field generated by the speakers test. The variability of the SPLs that directly impacts the structural responses (see discussion later in this section) is not confined to specific distinct modes such as 100 Hz and 250 Hz as shown in Figure 6a, but is across broader frequency bands. These variations are in violation of typical flight qualification standards and can be assessed further by examining the OASPLs computed from the control microphones' time histories using 1-second time segments. The speakers control microphone test data plotted in 1-second time segments are shown in Figure 8a. The computed levels using individual control microphones and the average of eight (spatial average) must fall between  $\pm 1$  dB tolerances at any given time during the tests. Clearly it is not the case with the speakers test data. The spatial average OASPLs for the speakers test for this case is at the borderline with the lower tolerance limit. Often in flight qualification tests the dynamics test conductors rely only on the average OASPL such as the one shown in this figure without considering the variation amongst the individual control microphones. Such data are often considered acceptable. However, in the case of the individual microphones the SPLs are clustered in three different regions outside the tolerance limits. This is clearly in violation of the flight hardware qualification requirements, at least for NASA related missions, and this condition provides over test for those components closer to the region with the OASPL near 147 dB and under test for those components closer to the 143 dB region. Similar calculations are performed using the chamber control microphones as shown in Figure 8b, where all levels from the microphones fall between the test tolerances as is expected for a safe and proper acoustic qualification test.



**Figure 5:** The sound pressure spectra of control microphones used to control the field using: a) the speakers test and b) reverberant acoustic test. The speakers' spectral plots also show the levels from eight monitor microphones.

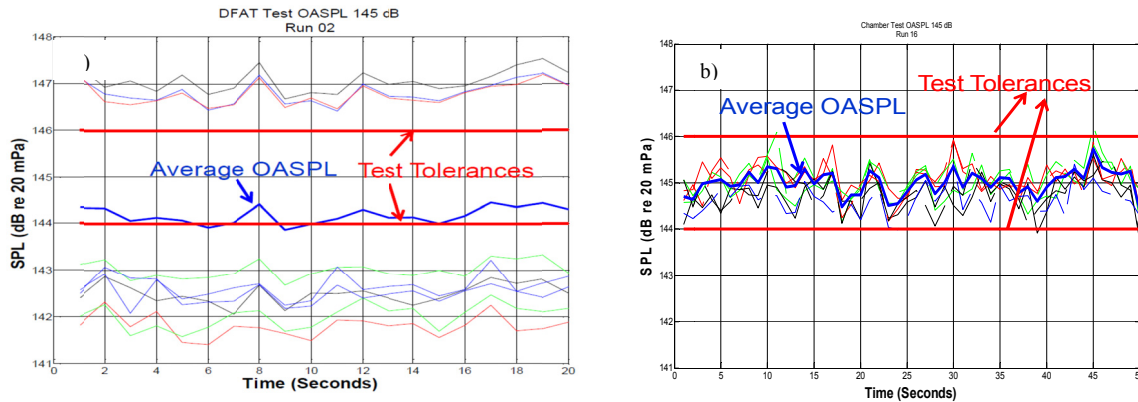


**Figure 6:** The SPLs measured using the speakers and reverberant acoustic testing are shown above. The averages of all microphones in the array are also shown here. The array was positioned in identical locations with respect to the test articles in these tests.



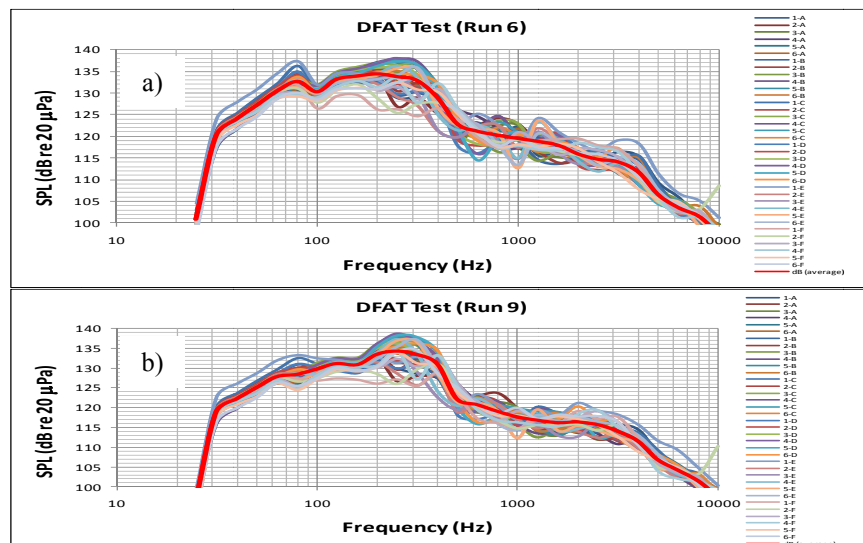
**Figure 7:** The SPLs in dB measured using the speakers (a) and reverberant (b) acoustic testing. Only data from one identical row of microphones in the array are plotted for the comparison purposes. The differences in the SPLs between the two tests are across all frequency bands.





**Figure 8:** The OASPLs measured using 8 control microphones from the speakers test (a) and from the reverberant acoustic test (b) computed over 1-second period. The average OASPLs of eight microphones and the test tolerances are also shown in these figures.

During the speaker testing a few runs were performed to assess the impact of the measured sound pressure levels on the control microphone locations. In one case, the control microphones were placed very close to the test articles (~8 inches). This provided some differences in the SPLs when compared with the case where the control microphones were located away from surfaces (See Figures 9a&b, with test articles). The control microphone locations of the SPLs shown in Figure 9a (Run 6) are identical to those discussed earlier (Figure 6a, without test articles), whereas, the SPLs shown in Figure 9b is identical to Figure 9a, except the microphones were about 8 inches from the test articles' surfaces. In general, it is recommended, as emphasized in NASA handbook<sup>9</sup>, that the location of control microphones be kept away from any surfaces by at least 2-ft. The SPLs measured by microphones closer to the hardware can influence the sound field with the test articles' potential sound radiating and/or absorbing capabilities<sup>10</sup>. The option of trying to tailor the control sound field to a specific environment by using control microphone locations is not technically justifiable. *It is highly recommended that the location of control microphones should not be used to tailor the sound field to meet a specific requirement.*

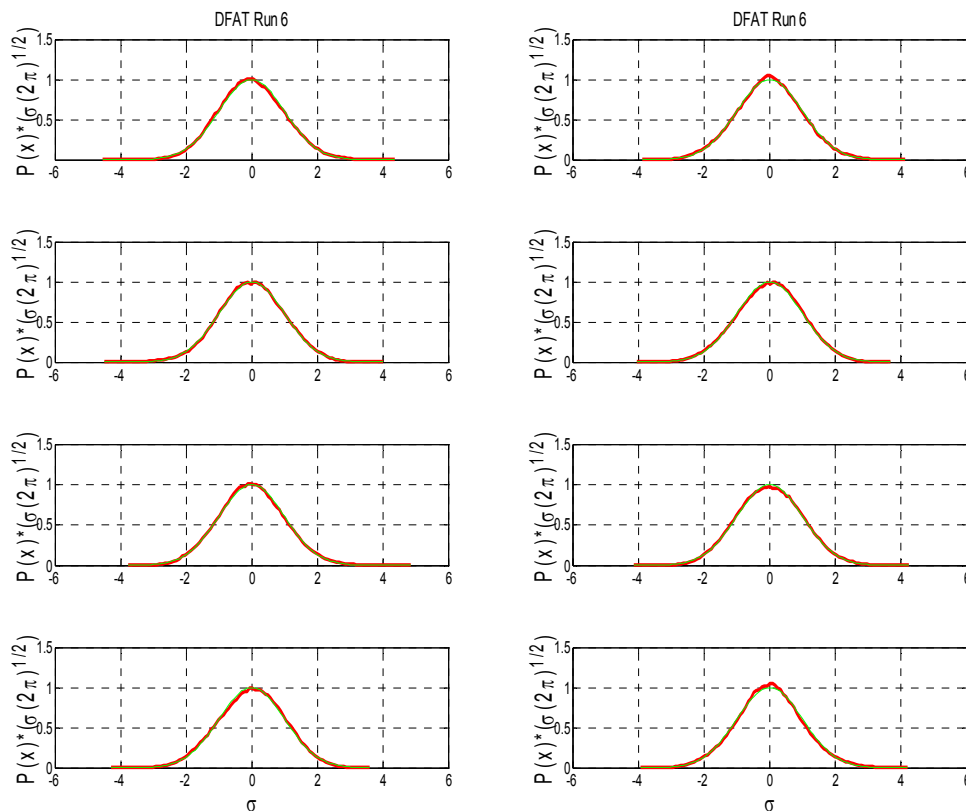


**Figure 9:** The SPLs measured using the speakers test with test articles for two control microphone locations; a) the control microphones were placed in identical locations as Figure 6a, and b) the control microphones were moved closer to the test articles (~8-inch). These data include the test articles within the speakers testing volume.



## SOUND PRESSURE DISTRIBUTIONS

It has been reported that the stationary random sound pressure levels measured using speaker tests may not behave as normal (Gaussian) distribution<sup>11</sup> as is expected from the data obtained using the reverberant chamber and any other random vibration tests. The sound pressure data from eight control microphones of Run 6 that included the test articles (OASPL of 140 dB using a time segment close to 20 seconds) were processed to obtain the distributions. Figure 10 shows the probability distribution of the peak pressure from eight control microphones plotted against sigma (peak/rms). Also plotted in this figure are the theoretical normal (Gaussian) distributions including the data high pass filtered at 1000 Hz. The un-filtered and filtered data are close to Gaussian distributions with the skewness and Kurtosis close to 0 and 3, respectively. However, the departure from Gaussian distribution is in having higher than 3sigma events occurring with much more frequency than predicted over the 20-second testing period. This has been observed in reverberant acoustic, structural random excitation, and random vibration testing<sup>12</sup>.



**Figure 10:** The probability of the peak pressure distributions (both filtered and unfiltered pressure) of the eight control microphones from Run 6. The measured pressure data follow near Gaussian distribution, except with occurrences of higher than 3sigma in a short testing period obtained using the extreme peak/rms of the pressure time history data.

## STRUCTURAL RESPONSES: REVERBERANT CHAMBER VS. SPEAKERS

The pressure variations between the speaker and reverberant testing were discussed in the previous section. As discussed earlier the aluminum panel and the cylinder were instrumented with enough sensors to make a quantitative comparison of the responses obtained from these methods of testing. The panel structural responses, for example, measured by accelerometers at

two locations on panel are shown in Figures 11a&b. In these figures data from three cases are shown. Two cases obtained from the speakers tests (corresponding SPLs shown in Figures 9a&b) and the third case is identical test condition with identical accelerometer locations but was obtained from the reverberant chamber test. These figures convey a few important findings related to the two methods of acoustic testing. For the speakers' tests (Runs 6 and 9) there are significant differences in the SPLs as shown in Figures 9a&b and so are the structural responses as shown in Figures 11a&b. The structural responses are much higher in speakers testing than they are in the reverberant testing for the same test articles and the required sound pressure levels. The increase in the  $g_{rms}$  by more than 6 dB must raise structural health concern if such conditions are produced when flight hardware is being qualified using speakers testing. Finally, the increase in structure responses compared to the relative increase in sound pressure levels do not correspond to the same changes. For example, consider structural modes between 50 to 200 Hz, shown in Figure 11a, which have 12 to 22 dB structural response differences as compared to the reverberant test. The peak-to-peak pressure dBs at this frequency range measured using the array are only between 5 to 10 dB. It is believed that there may be acoustic standing waves that give rise to the increase in the structural responses as was discussed in the paper by Kolaini et al<sup>2</sup>. The acoustic field changes in some frequencies that impact the structure may also be due to the wave interferences. A similar argument can be made for the acceleration responses measured at a different location on the panel. More detailed investigation of these observations is currently being made. The comparisons of the structural responses measured on the cylinder (See Figures 12a&b) provide similar behavior as the panel. In another speakers test recently performed using a simple panel similar differences in the structural responses were observed<sup>7</sup>. However, the speakers test discussed in the paper had a limited number of speakers with large gaps between the speaker stacks that may have provided a more complex acoustic field, due to the leakage, than the case discussed in this paper.

There has been some speculation within the aerospace community that, even though there may be differences in the SPLs measured using speakers tests, the structural responses on the average are not impacted significantly. To examine the differences in sound pressure levels and their impacts on the structural responses, the force responses obtained by force gages at four electronic box and panel interfaces in speakers and reverberant testing are compared in Figure 13. The differences in the force responses are very clear in this figure. The rms force from speakers tests is approximately 6 dB higher than the same in the reverberant test measurements. This example provides compelling proof that the differences in the sound pressure field and the spatial variability in speakers' testing have a profound effect on the structural loads transmitted to the components.

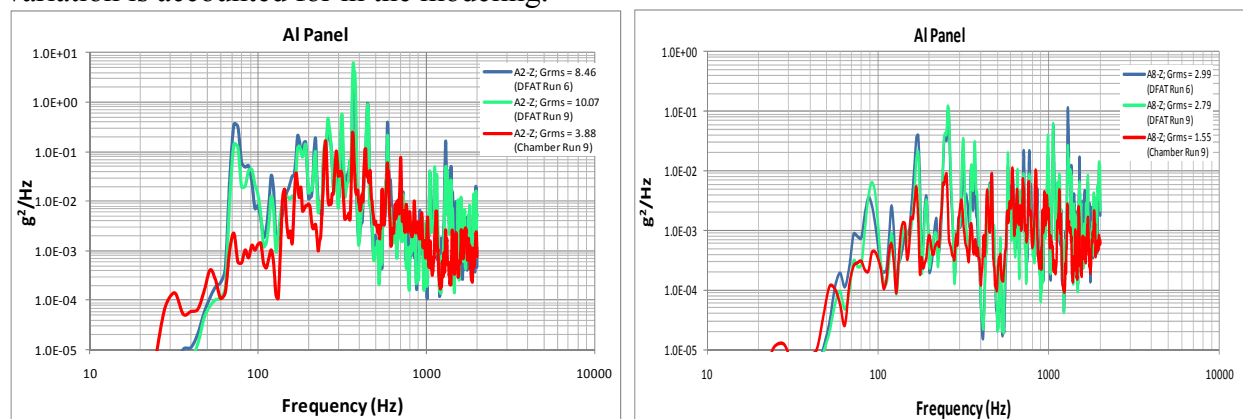
## SUMMARY AND CONCLUSIONS

Even though more than 100 flight qualification acoustic tests have so far been performed within the last several years using various speakers testing set ups, the knowledge of our understanding of the kind of acoustic field produced by this method of testing has been very minimal. It was the speakers' tests performed at JPL with the involvement from several institutions that provided an opportunity to examine the sound fields in a limited manner. The chief concern with this method of testing is producing acoustic fields with significant spatial variability that can impact the structural qualification in a significant way. The spatial sound pressure and structural

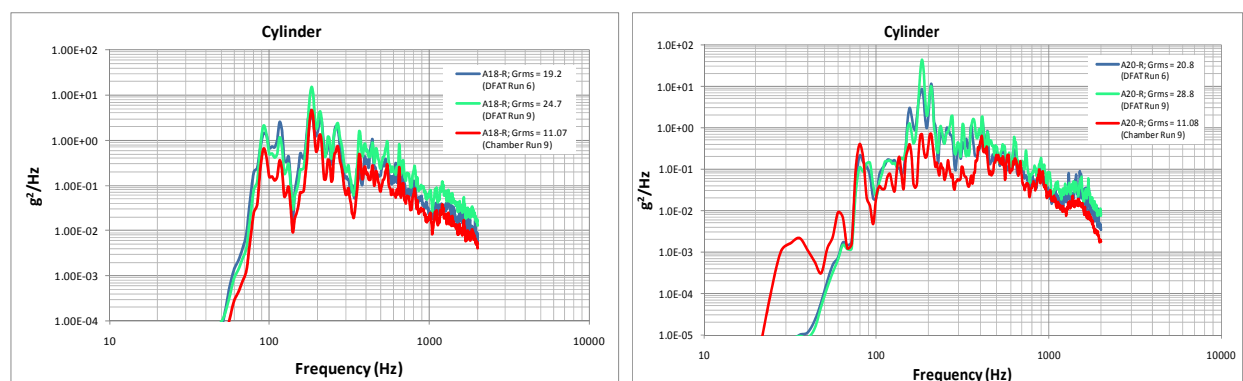
response variability of the speakers' tests compared with the reverberant test performed under similar conditions provide an alarming concern and if continued without fundamental changes in the approach flight hardware failure will occur. Our recommendation to the aerospace community is to avoid using the speaker testing until fundamental changes have been made. The new approach of controlling the speakers using MIMO is an improvement in the right direction. However, the acoustic field generated using MIMO control scheme must also go through the development phases before implementing it into qualifying the flight hardware.

Acoustic standing waves, wave interferences, proximity of the speakers to the flight hardware, control microphones re-arrangements to tailor the pressure field, etc. are parameters that will impact the generated field and should be examined before a sensitive hardware is acoustically tested using speakers. Another issue that may be important for some of the flight hardware is the exposure of the flight hardware to particulate in the testing area. This issue should also be addressed to minimize the flight hardware unwanted and unnecessary structural risk.

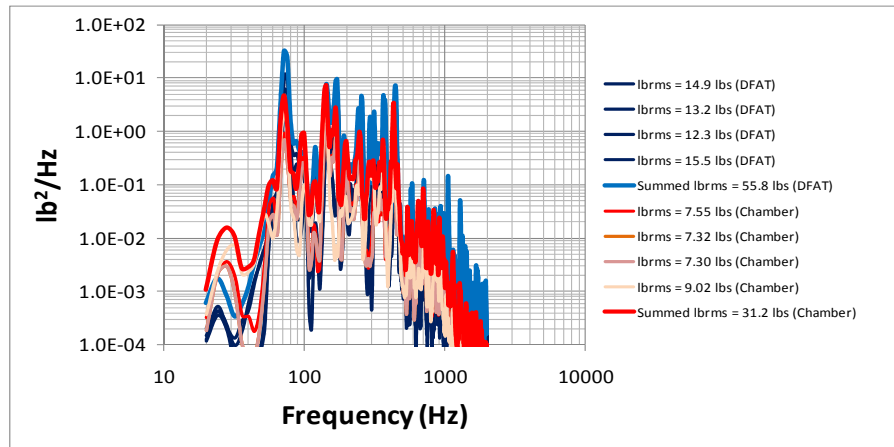
Finally, the vibro-acoustic analysis is often performed on spacecraft and/or acoustically responsive structures prior to testing. The model correlation is performed once the structural response measurements become available. For the kind of differences reported in this paper for both the pressure field and the structural responses, the vibro-acoustic model correlation will not be possible unless the acoustic field is characterized and the physics attributing to the spatial variation is accounted for in the modeling.



**Figure 11:** Acceleration panel responses measured at two locations using reverberant (red lines) and speakers tests (green and blue lines). The differences between two methods of testing for the same conditions are very clear.



**Figure 12:** Acceleration cylinder responses measured at two locations using reverberant (red lines) and speakers tests (green and blue lines). The differences between two methods of testing for the same conditions are very clear.



**Figure 13:** Force responses measured at the aluminum panel and electronic box interfaces obtained from both reverberant test (red lines) and speakers' tests (green and blue lines) are shown in this figure. The differences between two methods of acoustic testing for the same conditions are very clear, whether the summed force and/or individual interface forces are considered.

## ACKNOWLEDGMENT

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## **BIOGRAPHIES**

Dr. Ali R. Kolaini has been a Member of the Technical Staff at JPL since 2005. He currently has a position as a Principal Engineer in the Dynamics Environments group of the Mechanical Systems Division. Prior to joining JPL, Dr. Kolaini was an Engineering Specialist at The Aerospace Corporation, an associate professor at the University of Mississippi. He has a B.S. degree in Mechanical Engineering from the Lawrence Tech University, and a M.S. and a Ph.D. in Mechanical Engineering from the University of California, Santa Barbara. He has more than 20 years of experience in the fields of vibration, shock, and acoustics.

Mr. Dennis Kern has worked in vibration, acoustic and shock prediction and testing for aerospace structures and components for 39 years. Since 1978, he has supervised the dynamics environments activities at the Jet Propulsion Laboratory, supporting all JPL flight projects and managing numerous technology development programs. Mr. Kern has played a major role in the development of several NASA and industry standards and handbooks and has organized the annual NASA/USAF/Industry Spacecraft and Launch Vehicle Dynamics Environments Workshops since 1988.